

CHAPTER 16

STABILIZATION OF SUBGRADE SOILS

16-1. General.

a. The applicability and essential features of foundation soil treatments are summarized in tables 16-1 and 16-2 and in figure 16-1. The depth of stabilization generally must be sufficient to absorb most of the foundation pressure bulb.

b. The relative benefits of vibrocompaction, vibrodisplacement compaction, and precompression increase as load intensity decreases and size of loaded area increases. Soft, cohesive soils treated in place are generally suitable only for low-intensity loadings. Soil stabilization of wet, soft soils may be accomplished by addition of lime; grout to control water flow into excavations to reduce lateral support requirements or to reduce liquefaction or settlement caused by adjacent pile driving; seepage control by electroosmosis; and temporary stabilization by freezing. The range of soil grain sizes for which each stabilization method is most applicable is shown in figure 16-1.

16-2. Vibrocompaction. Vibrocompaction methods (blasting, terraprobe, and vibratory rollers) can be used for rapid densification of saturated cohesionless soils (fig 16-1). The ranges of grain-size distributions suitable for treatment by vibrocompaction, as well as vibroflotation, are shown in figure 16-2. The effectiveness of these methods is greatly reduced if the percent finer than the No. 200 sieve exceeds about 20 percent or if more than about 5 percent is finer than 0.002 millimeter, primarily because the hydraulic conductivity of such materials is too low to prevent rapid drainage following liquefaction. The usefulness of these methods in partly saturated sands is limited, because the lack of an increase of pore water pressure impedes liquefaction. Lack of complete saturation is less of a restriction to use of blasting because the high-intensity shock wave accompanying detonation displaces soil, leaving depressions that later can be backfilled.

a. *Blasting.*

(1) Theoretical design procedures for densification by blasting are not available and continuous on-site supervision by experienced engineers having authority to modify procedures as required is essential if this treatment method is used. A surface heave of about 6 inches will be observed for proper charge sizes and placement depths. Surface cratering should be avoided. Charge masses of less than 4 to more than 60 pounds

have been used. The effective radius of influence for charges using (M = lb) 60 percent dynamite is as follows:

$$R = 3M^{1/3} \text{ (feet)} \quad (16-1)$$

Charge spacings of 10 to 25 feet are typical. The center of charges should be located at a depth of about two-thirds the thickness of the layer to be densified, and three to five successive detonations of several spaced charges each are likely to be more effective than a single large blast. Little densification is likely to result above about a 3-foot depth, and loosened material may remain around blast points. Firing patterns should be established to avoid the "boxing in" of pore water. Free-water escape on at least two sides is desirable.

(2) If blasting is used in partly saturated sands or loess, preflooding of the site is desirable. In one technique, blast holes about 3 to 3 1/2 inches in diameter are drilled to the desired depth of treatment, then small charges connected by prima cord, or simply the prima cord alone, are strung the full depth of the hole. Each hole is detonated in succession, and the resulting large diameter holes formed by lateral displacement are backfilled. A sluiced-in cohesionless backfill will densify under the action of vibrations from subsequent blasts. Finer grained backfills can be densified by tamping.

b. *Vibrating probe (terraprobe).*

(1) A 30-inch-outside-diameter, open-ended pipe pile with 3/4-inch wall thickness is suspended from a vibratory pile driver operating at 15 Hz. A probe length 10 to 15 feet greater than the soil depth to be stabilized is used. Vibrations of 7%- to 1-inch amplitude are in a vertical mode. Probes are made at spacings of 3 to 10 feet. After sinkage to the desired depth, the probe is held for 30 to 60 seconds before extraction. The total time required per probe is typically 2 1/2 to 4 minutes. Effective treatment has been accomplished at depths of 12 to 60 feet. Areas in the range of 450 to 700 square yards may be treated per machine per 8-hour shift.

(2) Test sections about 30 to 60 feet on a side are desirable to evaluate the effectiveness and required probe spacing. The grain-size range of treated soil should fall within limits shown in figure 16-2. A square pattern is often used, with a fifth probe at the center of each square giving more effective increased densification than a reduced spacing. Saturated soil

	METHOD	PRINCIPLE	MOST SUITABLE SOIL CONDITIONS/TYPES	MAXIMUM EFFECTIVE TREATMENT DEPTH	ECONOMICAL SIZE OF TREATED AREA	SPECIAL MATERIALS REQUIRED	SPECIAL EQUIPMENT REQUIRED	PROPERTIES OF TREATED MATERIAL	SPECIAL ADVANTAGES AND LIMITATIONS	RELATIVE COSTS (1976)
VIBRO-COMPACTION	BLASTING	Shock waves and vibrations cause liquefaction, displacement, remolding	Saturated, clean sands; partly saturated sands and silts after flooding	60 ft	Small areas can be treated economically	Explosives, backfill to plug drill holes	Jetting or drilling machine	Can obtain relative densities to 70-80%; may get variable density	Rapid, inexpensive, can treat small areas; variable properties, no improvement near surface, dangerous	Low (\$0.50 \$1.00 per cu yd
	TERRAPROBE	Densification by vibration; liquefaction induced settlement under overburden	Saturated or dry clean sand	60 ft (Ineffective above 12 ft depth)	>1200 yd ²	None	Vibratory pile driver and 750 mm dia open steel pipe	Can obtain Relative Densities of 80% or more	Rapid, simple, good underwater; soft underlayers may damp vibrations, difficult to penetrate, stiff overlayers, not good in partly saturated soils	Moderate \$1.50- \$3.25 per cu yd \$2.00/cu yd average
	VIBRATORY ROLLERS	Densification by vibration; liquefaction induced settlement under roller weight	Cohesionless soils	6-10 ft	Any size	None	Vibratory roller	Can obtain very high relative densities; upper few decimeters not densified	Best method for thin layers or lifts	Low
VIBRO-DISPLACEMENT COMPACTION	COMPACTION PILES	Densification by displacement of pile volume and by vibration during driving	Loose sandy soils; partly saturated clayey soils; loess	60 ft	Small to moderate	Pile material (often sand or soil plus cement mixture)	Pile driver	Can obtain high densities, good uniformity	Useful in soils with fines, uniform compaction, easy to check results; slow, limited improvement in upper 1-2 m	High
	HEAVY TAMPING (Dynamic Consolidation)	Repeated application of high intensity impacts at surface	Cohesionless soils best, other types can also be improved	50-60 ft	>4000 yd ²	None	Tamper of 10-40 tons high capacity crane	Can obtain high relative densities, reasonable uniformity	Simple, rapid, suitable for some soils with fines; usable above and below water; requires control, must be away from existing structures	<Vibro-flotation
	VIBROFLOTATION	Densification by vibration and compaction of backfill material	Cohesionless soils with less than 20% fines	90 ft	>1200 yd ²	Granular backfill	Vibroflot, crane	Can obtain high relative densities, good uniformity	Useful in saturated and partly saturated soils, uniformity	\$10.00-\$25.00/yd \$1.00/cu yd May be about half compaction piles or concrete piles

(Continued)

(Sheet 1 of 5)

Table 16-1. Stabilization of Soils for Foundations of Structures

	METHOD	PRINCIPLE	MOST SUITABLE SOIL CONDITIONS/TYPES	MAXIMUM EFFECTIVE TREATMENT DEPTH	ECONOMICAL SIZE OF TREATED AREA	SPECIAL MATERIALS REQUIRED	SPECIAL EQUIPMENT REQUIRED	PROPERTIES OF TREATED MATERIAL	SPECIAL ADVANTAGES AND LIMITATIONS	RELATIVE COSTS (1976)
GROUTING AND INJECTION	PARTICULATE GROUTING	Penetration grouting-fill soil pores with soil, cement, and/or clay	Medium to coarse sand and gravel	Unlimited	Small	Grout, water	Mixers, tanks, pumps, hoses	Impervious, high strength with cement grout, eliminate liquefaction danger	Low cost grouts, high strength; limited to coarse-grained soils, hard to evaluate	Lowest of the grout systems
	CHEMICAL GROUTING	Solutions of two or more chemicals react in soil pores to form a gel or a solid precipitate	Medium silts and coarser	Unlimited	Small	Grout, water	Mixers, tanks, pumps, hoses	Impervious, low to high strength, eliminate liquefaction danger	Low viscosity, controllable gel time, good water shut-off; high cost, hard to evaluate	High to very high \$30/m ³ min-\$80/m ³ typical
	PRESSURE INJECTED LIME	Lime slurry injected to shallow depths under high pressure	Expansive clays	Unlimited, but 2-3 m usual	Small	Lime, water, surfactant	Slurry tanks, agitators, injection	Lime encapsulated zones formed by channels resulting from cracks, root holes, hydraulic fracture	Rapid and economical treatment for foundation soils under light structures	\$2.50 to \$3.00/m ² of ground surface area
	DISPLACEMENT GROUT	Highly viscous grout acts as radial hydraulic jack when pumped in under high pressure	Soft, fine-grained soils; foundation soils with large voids or cavities	Unlimited, but a few m usual	Small	Soil, cement, water	Batching equipment, high pressure pumps, hoses	Grout bulbs within compressed soil matrix	Good for correction of differential settlements, filling large voids; careful control required	Low material, high injection
	ELECTROKINETIC INJECTION	Stabilizing chemicals moved into soil by electro-osmosis	Saturated silts, silty clays	Unknown	Small	Chemical stabilizer	DC power supply, anodes, cathodes	Increased strength, reduced compressibility	Existing soil and structures not subjected to high pressures; no good in soil with high conductivity	Expensive

(Continued)

(Sheet 2 of 5)

Table 16-1. Stabilization of Soils for Foundations of Structures-Continued

	METHOD	PRINCIPLE	MOST SUITABLE SOIL CONDITIONS/TYPES	MAXIMUM EFFECTIVE TREATMENT DEPTH	ECONOMICAL SIZE OF TREATED AREA	SPECIAL MATERIALS REQUIRED	SPECIAL EQUIPMENT REQUIRED	PROPERTIES OF TREATED MATERIAL	SPECIAL ADVANTAGES AND LIMITATIONS	RELATIVE COSTS (1976)
PRECOMPRESSION	PRELOADING	Load is applied sufficiently in advance of construction so that compression of soft soils is completed prior to development of the site	Normally consolidated soft clays, silts, organic deposits, completed sanitary landfills	-----	>1000 m ²	Earth fill or other material for loading the site; sand or gravel for drainage blanket	Earth moving equipment; large water tanks or vacuum drainage systems sometimes used; settlement markers, piezometers	Reduced water content and void ratio, increased strength	Easy, theory well developed, uniformity; requires long time (sand drains or wicks can be used to reduce consolidation time)	Low (Moderate if vertical drains are required)
	SURCHARGE FILLS	Fill in excess of that required permanently is applied to achieve a given amount of settlement in a shorter time; excess fill then removed	Normally consolidated soft clays, silts, organic deposits, completed sanitary landfills	-----	>1000 m ²	Earth fill or other material for loading the site; sand or gravel for drainage blanket	Earth moving equipment; settlement markers, piezometers	Reduced water content, void ratio and compressibility; increased strength	Faster than preloading without surcharge, theory well developed; extra material handling; can use sand drains or wicks	Moderate. Sand drains cost \$3.30-\$6.60/m
	DYNAMIC CONSOLIDATION	High energy impacts compress and dissolve gas in pores to give immediate settlement; increased pore pressure gives subsequent drainage	Partly saturated fine grained soils, quaternary clays with 1-4 gas in micro bubbles	20 m	>15000-30000 m ²	None	Tamper of 10-40 tons, high capacity crane	Reduced water content, void ratio and compressibility; increased strength	Faster than preloading, economical on large areas; uncertain mechanism in clays, less uniformity than preloading	<preload fills with sand drains
	ELECTRO-OSMOSIS	DC current causes water flow from anode towards cathode where it is removed	Normally consolidated silts and silty clays	10-20 m	Small	Anodes (usually re-bars or aluminum), cathodes (well points or re-bars)	DC power supply, wiring, metering systems	Reduced water content and compressibility, increased strength, electrochemical hardening	No fill loading required, can use in confined area, relatively fast; non-uniform properties between electrodes, no good in highly conductive soils	High

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(Sheet 3 of 5)

Table 16-1. Stabilization of Soils for Foundations of Structures-Continued

	METHOD	PRINCIPLE	MOST SUITABLE SOIL CONDITIONS/TYPES	MAXIMUM EFFECTIVE TREATMENT DEPTH	ECONOMICAL SIZE OF TREATED AREA	SPECIAL MATERIALS REQUIRED	SPECIAL EQUIPMENT REQUIRED	PROPERTIES OF TREATED MATERIAL	SPECIAL ADVANTAGES AND LIMITATIONS	RELATIVE COSTS (1976)
REINFORCEMENT	MIX-IN-PLACE PILES AND WALLS	Lime, cement, or asphalt introduced through rotating auger or special in-place mixer	All soft or loose inorganic soils	>20 m	Small	Cement, lime, asphalt, or chemical stabilizer	Drill rig, rotary cutting and mixing head, additive proportioning equipment	Solidified soil piles or walls of relatively high strength	Uses native soil, reduced lateral support requirements during excavation; difficult quality control	Moderate to high
	STRIPS AND MEMBRANES	Horizontal tensile strips or membranes buried in soil under footings	All	A few m	Small	Metal or plastic strips, polyethylene, polypropylene or polyester fabrics	Excavating, earth handling, and compaction equipment	Increased bearing capacity, reduced deformations	Increased allowable bearing pressure; requires over-excavation for footings	Low to Moderate
	VIBRO-REPLACEMENT STONE COLUMNS	Hole jetted into soft, fine-grained soil and back-filled with densely compacted gravel	Soft clays and alluvial deposits	20 m	>1500 m ²	Gravel or crushed rock backfill	Vibroflot, crane or Vibrocat, water	Increased bearing capacity, reduced settlements	Faster than pre-compression, avoids dewatering required for remove and replace; limited bearing capacity	Moderate to high ~\$30/m; >pile penetration
THERMAL	HEATING	Drying at low temperatures; alteration of clays at intermediate temperatures (400-600°C); fusion at high temperatures (>1000°C)	Fine-grained soils, especially partly saturated clays and silts, loess	15 m	Small	Fuel	Fuel tanks, burners, blowers	Reduced water control, plasticity, water sensitivity; increased strength	Can obtain irreversible improvements in properties; can introduce stabilizers with hot gases. Experimental	High
	FREEZING	Freeze soft, wet ground to increase its strength and stiffness	All soils	Several m	Small	Refrigerant	Refrigeration system	Increased strength and stiffness; reduced permeability	No good in flowing ground water, temporary	High

(Continued)

(Sheet 4 of 5)

Table 16-1. Stabilization of Soils for Foundations of Structures-Continued

	METHOD	PRINCIPLE	MOST SUITABLE SOIL CONDITIONS/TYPES	MAXIMUM EFFECTIVE TREATMENT DEPTH	ECONOMICAL SIZE OF TREATED AREA	SPECIAL MATERIALS REQUIRED	SPECIAL EQUIPMENT REQUIRED	PROPERTIES OF TREATED MATERIAL	SPECIAL ADVANTAGES AND LIMITATIONS	RELATIVE COSTS (1976)
MISCELLANEOUS	REMOVE AND REPLACE (with or without admixtures)	Foundation soil excavated, improved by drying or admixture, and recompacted	Inorganic soils	10 m ?	Small	None, unless admixture stabilizers used	Excavating and compaction equipment, dewatering system	Increased strength and stiffness, reduced compressibility	Uniform, controlled foundation soil when replaced; may require large area dewatering	High
	MOISTURE BARRIERS	Water access to foundation soils is prevented	Expansive soils	5 m	Small	Membranes, gravel, lime, or asphalt	Excavating and trenching equipment, compaction equipment	Initial natural or as-compacted properties retained	Best for small structures; may not be 100% effective	Low to moderate
	PREWETTING	Soil is brought to estimated final water content prior to construction	Expansive soils	2-3 m	Small	Water	None	Decreased swelling potential	Low cost, best for small, light structures, may still get shrinking and swelling	Low
	STRUCTURAL FILLS (with or without admixtures)	Structural fill distributes loads to underlying soft soils	Use over soft clays or organic soils, marsh deposits	-----	Small	Sand, gravel, flyash, bottom ash, slag, expanded aggregate, clam shell or oyster shell, incinerator ash	Compaction equipment	Soft subgrade protected by structural load-bearing fill	High strength, good load distribution to underlying soft soils	Moderate to high (\$12/m ³)

(Sheet 5 of 5)

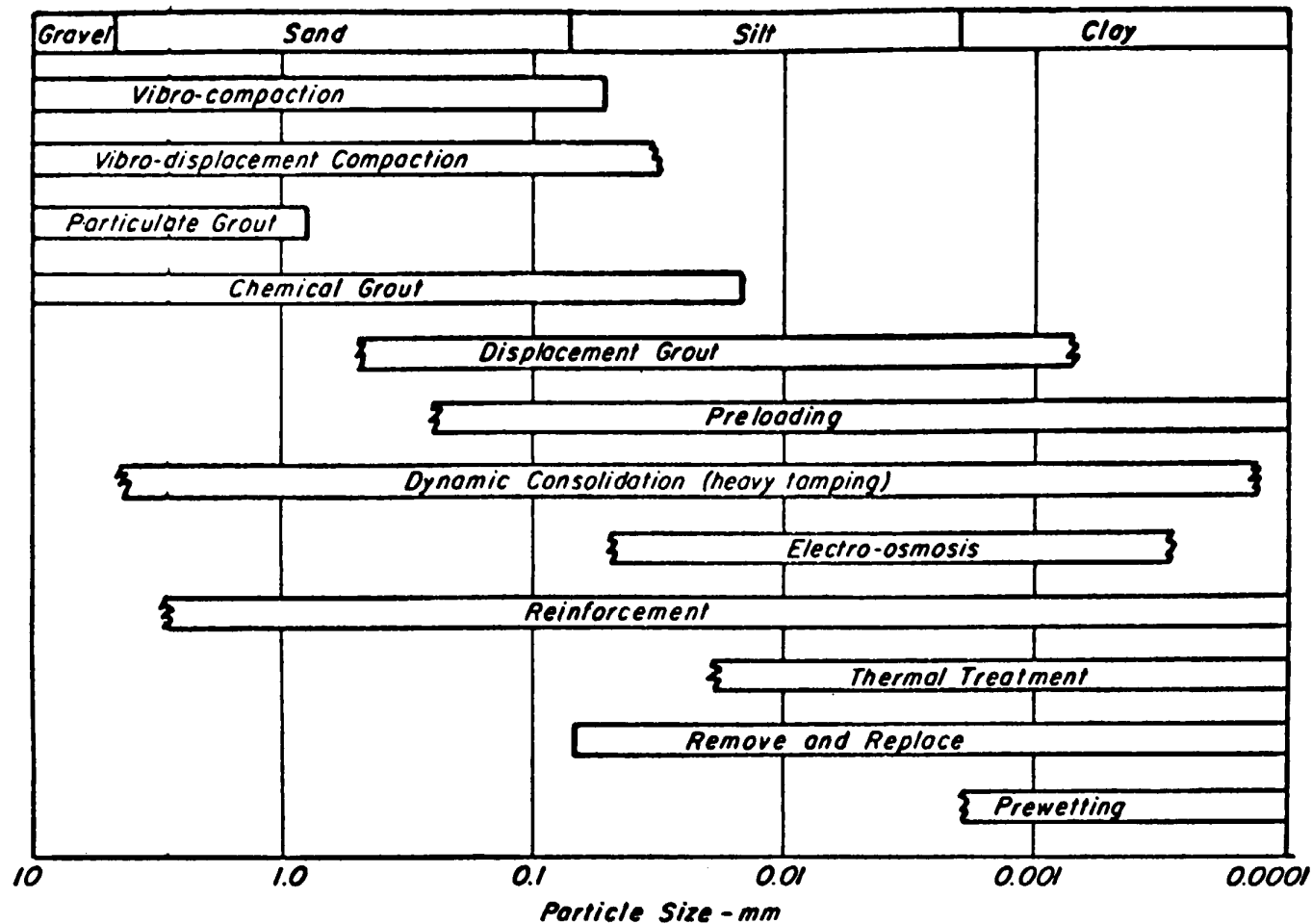
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Table 16-1. Stabilization of Soils for Foundations of Structures-Continued

CATEGORY OF STRUCTURE	STRUCTURE	PERMISSIBLE SETTLEMENT	LOAD INTENSITY/ USUAL BEARING PRESSURE REQUIRED (tsf)	Probability of Advantageous Use of Soil Improvement Techniques		
				LOOSE COHESION- LESS SOILS	SOFT ALLUVIAL DEPOSITS	OLD, INORGANIC FILLS
OFFICE/ APARTMENT FRAME OR LOAD- BEARING CONSTRUCTION	High rise: More than 6 stories	Small <25-50 mm	High (3+1)	High	Unlikely	Low
	Medium rise: 3-6 stories	Small <25-50 mm	Moderate (2)	High	Low	Good
	Low rise: 1-3 stories	Small <25-50 mm	Low (1-2)	High	Good	High
INDUSTRIAL	Large span w/heavy machines, cranes; process plants; power plants	Small (<25-50 mm) Differential settlement Critical	Variable/high local concentrations to >4	High	Unlikely	Low
	Framed warehouses and factories	Moderate	Low (1-2)	High	Good	High
	Covered storage, stor. rack systems, production areas	Low to moderate	Low (<2)	High	Good	High
OTHERS	Water and waste water treatment plants	Moderate Differential settlement Important	Low/<150 (<1.5)	High, if required at all	High	High
	Storage tanks	Moderate to high, but differential, may be critical	High/up to 300 (3)	High, if required at all	High	High
	Open storage areas	High	High/up to 300 (3)	High, if required at all	High	High
	Embankments and abutments	Moderate to high	High/up to 200 (2)	High, if required at all	High	High

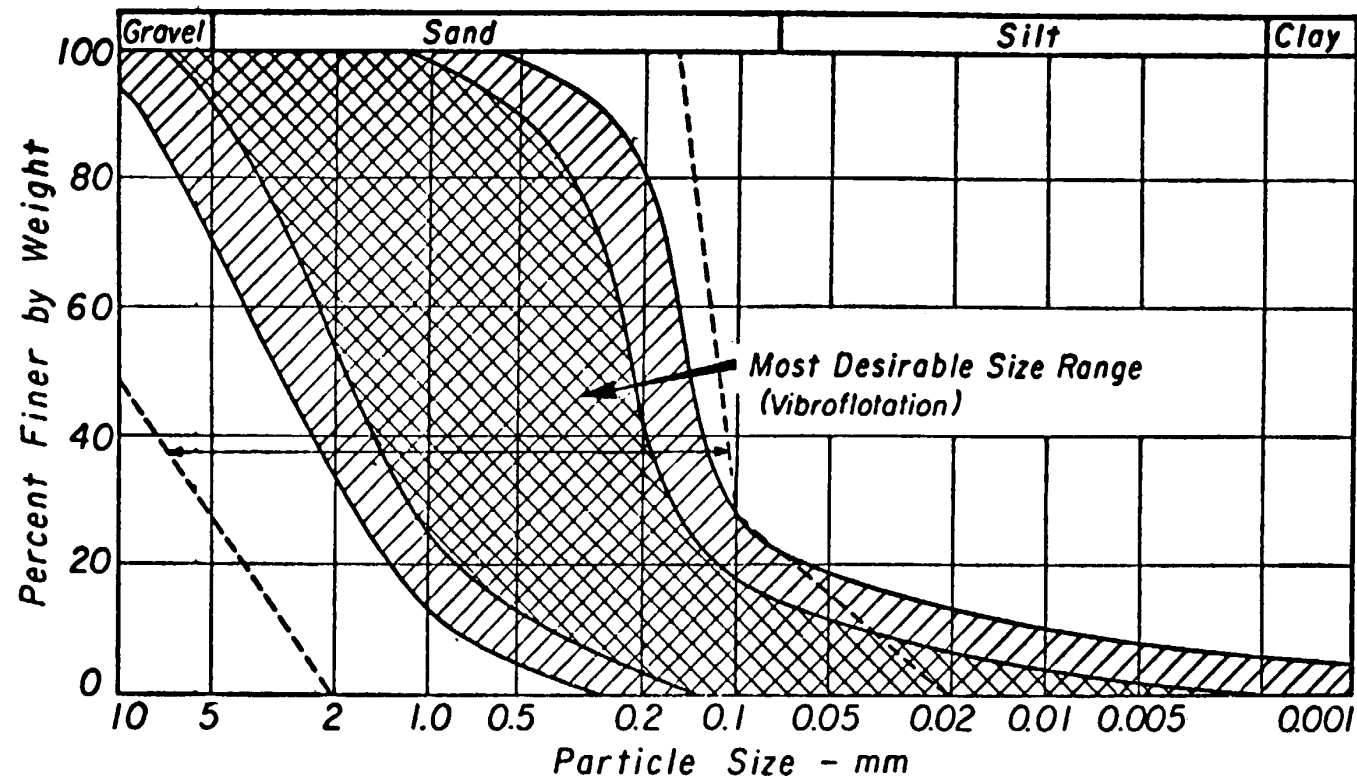
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Table 16-2. Applicability of Foundation Soil Improvement for Different Structures and Soil Types (for efficient use of Shallow Foundations)



(Courtesy of J. K. Mitchell, "Innovations in Ground Stabilization," Chicago Soil Mechanics Lecture Series, Innovations in Foundation Construction, Illinois Section, 1972. Reprinted by permission of The American Society of Civil Engineers, New York.)

Figure 16-1. Applicable grain-size ranges for different stabilization methods.



(Courtesy of J. K. Mitchell, "Innovations in Ground Stabilization," Chicago Soil Mechanics Lecture Series, Innovations in Foundation Construction, Illinois Section, 1972. Reprinted by permission of The American Society of Civil Engineers, New York.)

Figure 16-2. Range of particle-size distributions suitable for densification by vibrocompaction.

conditions are necessary. Underlying soft clay layers may dampen vibrations.

c. *Vibratory rollers.* Where cohesionless deposits are of limited thickness, e.g., less than 6 feet, or where cohesionless fills are being placed, vibratory rollers are likely to be the best and most economical means for achieving high density and strength. Use with flooding where a source of water is available. The effective depth of densification may be 6 feet or more for the heaviest vibratory rollers (fig 16-3a). For a fill placed in successive lifts, a density-depth distribution similar to that in figure 16-3b results. It is essential that the lift thickness, soil type, and roller type be matched. Properly matched systems can yield compacted layers at a relative density of 85 to 90 percent or more.

16-3. Vibrodisplacement compaction. The methods in this group are similar to those described in the preceding section except that the vibrations are supplemented by active displacement of the soil and, in the case of vibroflotation and compaction piles, by backfilling the zones from which the soil has been displaced.

a. *Compaction piles.* Partly saturated or freely draining soils can be effectively densified and strengthened by this method, which involves driving displacement piles at close spacings, usually 3 to 6 feet on centers. One effective procedure is to cap temporarily the end of a pipe pile, e.g., by a detachable plate, and drive it to the desired depth, which may be up to 60 feet. Either an impact hammer or a vibratory driver can be used. Sand or other backfill material is introduced in lifts with each lift compacted concurrently with withdrawal of the pipe pile. In this way, not only is the backfill compacted, but the compacted column has also expanded laterally below the pipe tip forming a caisson pile.

b. *Heavy tamping (dynamic consolidation).*

(1) Repeated impacts of a very heavy weight (up to 80 kips) dropped from a height of 50 to 130 feet are applied to points spaced 15 to 30 feet apart over the area to be densified. In the case of cohesionless soils, the impact energy causes liquefaction followed by settlement as water drains. Radial fissures that form around the impact points, in some soils, facilitate drainage. The method has been used successfully to treat soils both above and below the water table.

(2) The product of tamper mass and height of fall should exceed the square of the thickness of layer to be densified. A total tamping energy of 2 to 3 blows per square yard is used. Increased efficiency is obtained if the impact velocity exceeds the wave velocity in the liquefying soil. One crane and tamper can treat from 350 to 750 square yards per day. Economical use of the method in sands requires a minimum treatment area of 7500 square yards. Relative densities of 70 to 90

percent are obtained. Bearing capacity increases of 200 to 400 percent are usual for sands and marls, with a corresponding increase in deformation modulus. The cost is reported as low as one-fourth to one-third that of vibroflotation.

(3) Because of the high-amplitude, low-frequency vibrations (2-12 Hz), minimum distances should be maintained from adjacent facilities as follows:

Piles or bridge abutment	15-20 feet
Liquid storage tanks	30 feet
Reinforced concrete buildings	50 feet
Dwellings	100 feet
Computers (not isolated)	300 feet

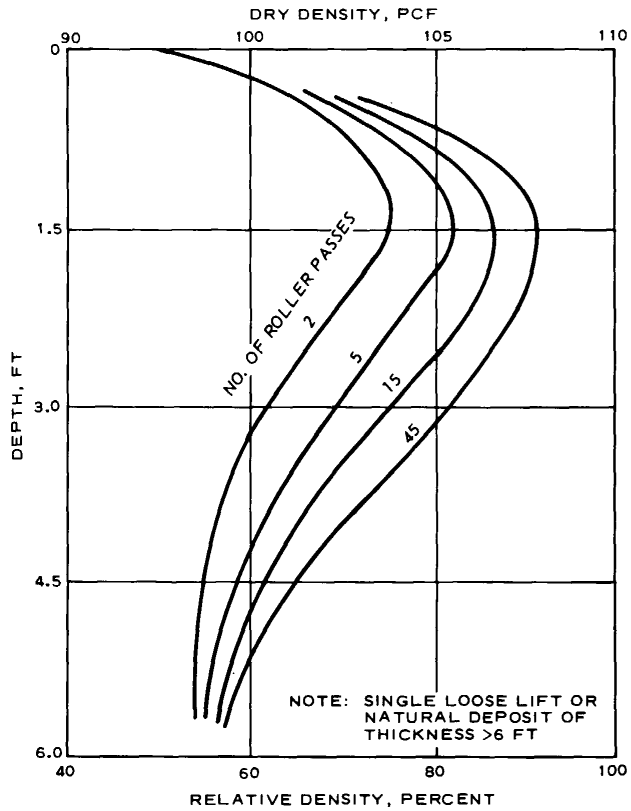
c. *Vibroflotation.*

(1) A cylindrical penetrator about 15 inches in diameter and 6 feet long, called a vibroflot, is attached to an adapter section containing lead wires and hoses. The whole assembly is handled by a crane. A rotating eccentric weight inside the vibroflot develops a horizontal centrifugal force of about 10 tons at 1800 revolutions per minute. Total weight is about 2 tons.

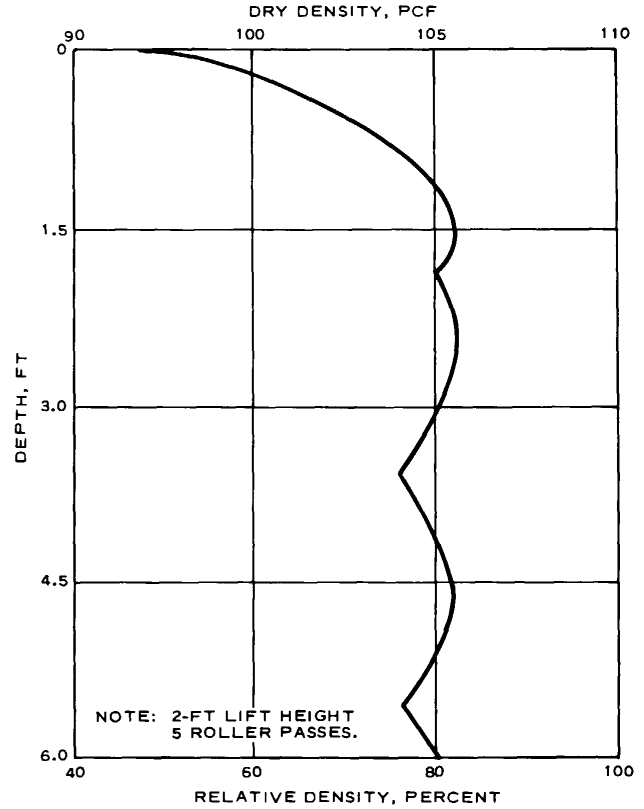
(2) To sink the vibroflot to the desired treatment depth, a water jet at the tip is opened and acts in conjunction with the vibrations so that a hole can be advanced at a rate of about 3.6 feet per minute; then the bottom jet is closed, and the vibroflot is withdrawn at a rate of about 0.1 foot per minute. Newer, heavier vibroflots operating at 100 horsepower can be withdrawn at twice this rate and have a greater effective penetration depth. Concurrently, a cohesionless sand or gravel backfill is dumped in from the ground surface and densified. Backfill consumption is at a rate of about 0.7 to 2 cubic yards per square yard of surface. In partly saturated sands, water jets at the top of the vibroflot can be opened to facilitate liquefaction and densification of the surrounding ground. Liquefaction occurs to a radial distance of 1 to 2 feet from the surface of the vibroflot. Most vibroflotation applications have been to depths less than 60 feet, although depths of 90 feet have been attained successfully.

(3) A relationship between probable relative density and vibroflot hold spacings is given in figure 16-4. Newer vibroflots result in greater relative densities. Figure 16-5 shows relationships between allowable bearing pressure to limit settlements to 1 inch and vibroflot spacing. Allowable pressures for "essentially cohesionless fills" are less than for clean sand deposits, because such fills invariably contain some fines and are harder to densify.

(4) Continuous square or triangular patterns are often used over a building site. Alternatively, it may be desired to improve the soil only at the locations of individual spread footings. Patterns and spacings required for an allowable pressure of 3 tons per square foot and square footings are given in table 16-3.



a. DENSITY VERSUS DEPTH FOR DIFFERENT NUMBERS OF ROLLER PASSES



b. DENSITY VERSUS DEPTH RELATIONSHIP FOR A SERIES OF 2-FT LIFTS

Figure 16-3. Sand densification using vibratory rollers.

16-4. Grouting and injection. Grouting is a high-cost soil stabilization method that can be used where there is sufficient confinement to permit required injection pressures. It is usually limited to zones of relatively small volume and to special problems. Some of the more important applications are control of groundwater during construction; void filling to prevent excessive settlement; strengthening adjacent foundation soils to protect against damage during excavation, pile driving, etc.; soil strengthening to reduce lateral support requirements; stabilization of loose sands against liquefaction; foundation underpinning; reduction of machine foundation vibrations; and filling solution voids in calcareous materials.

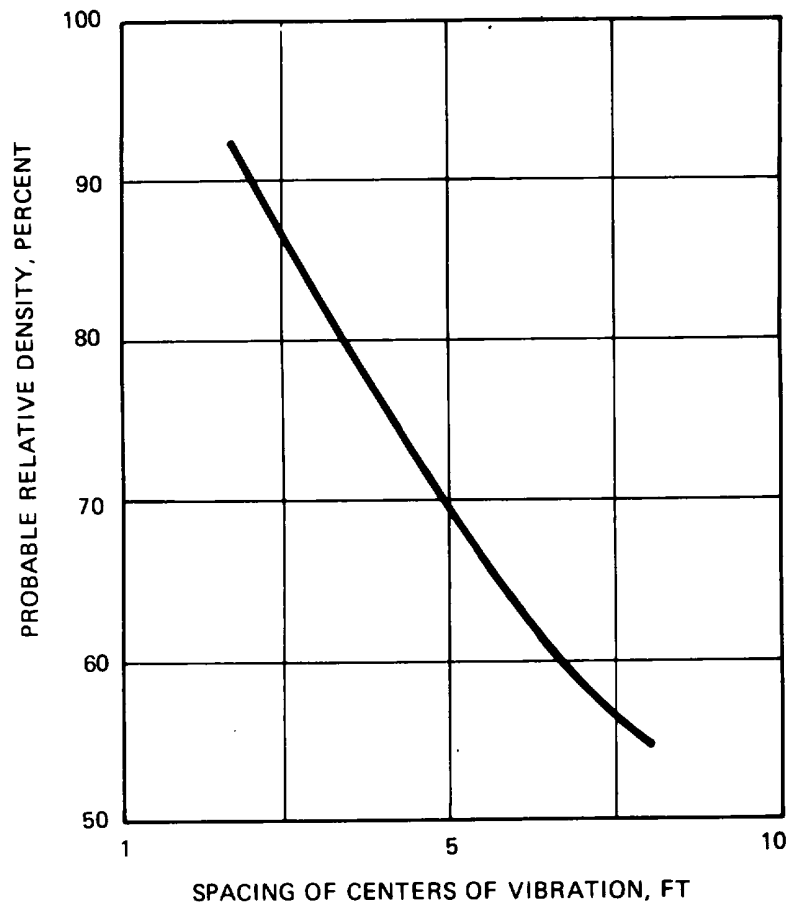
a. Grout types and groutability. Grouts can be classified as particulate or chemical. Portland cement is the most widely used particulate grouting material. Grouts composed of cement and clay are also widely used, and lime-slurry injection is finding increasing application. Because of the silt-size particles in these materials, they cannot be injected into the pores of soils finer than medium to coarse sand. For successful grouting of soils, use the following guide

$$\frac{(D_{15})_{\text{soil}}}{(D_{85})_{\text{grout}}} > 25$$

Type I portland cement, Type II portland cement, and Type III portland cement, Type III portland cement, and processed bentonite cannot be used to penetrate soils finer than 30, 40, and 60 mesh sieve sizes, respectively. Different types of grouts may be combined to both coarse- and fine-grained soils.

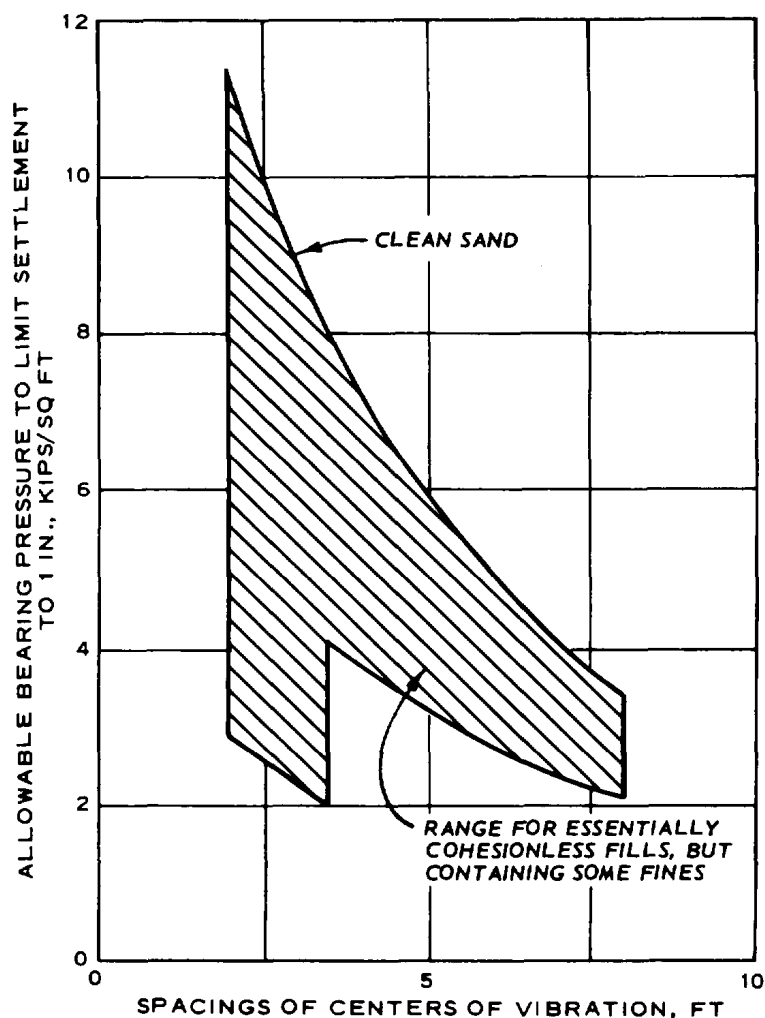
b. Cement and soil-cement grouting. See TM 5-818-6/AFM 88-32 for discussion of planning and implementation of foundation grouting with cement and soil-cement.

c. Chemical grouting. To penetrate the voids of finer soils, chemical grout must be used. The most common classes of chemical grouts in current use are silicates, resins, lignins, and acrylamides. The viscosity of the chemical-water solution is the major factor controlling groutability. The particle-size ranges over



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Figure 16-4. Relative density as a function of vibroflot hole spacings.



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Figure 16-5. Allowable bearing pressure on cohesionless soil layers stabilized by vibroflotation.

Table 16-3. Vibroflotation Patterns for Isolated Footings for an Allowable Bearing Pressure.

Square Footing Size, ft	Vibroflotation Points	Center to Center Spacing, ft	Pattern
4.0	1	---	---
4.5-5.5	2	6.0	Line
6-7	3	7.5	Triangle
7.5-9.5	4	6.0	Square
10-12	5	7.5	Square + 1 @ Center

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which each of these grout types is effective is shown in figure 16-6.

16-5. Precompression.

a. Preloading. Earth fill or other material is placed over the site to be stabilized in amounts sufficient to produce a stress in the soft soil equal to that anticipated from the final structures. As the time required for consolidation of the soft soil may be long (months to years), varying directly as the square of the layer thickness and inversely as the hydraulic conductivity, preloading alone is likely to be suitable only for stabilizing thin layers and with a long period of time available prior to final development of the site.

b. Surcharge fills. If the thickness of the fill placed for pre-loading is greater than that required to induce stresses corresponding to structure-induced stresses, the excess fill is termed a surcharge fill. Although the rate of consolidation is essentially independent of stress increase, the amount of consolidation varies approximately in proportion to the stress increase. It follows, therefore, that the preloading fill plus surcharge can cause a given amount of settlement in shorter time than can the preloading fill alone. Thus, through the use of surcharge fills, the time required for preloading can be reduced significantly.

(1) The required surcharge and loading period can be determined using conventional theories of consolidation. Both primary consolidation and most of the secondary compression settlements can be taken out in advance by surcharge fills. Secondary compression settlements may be the major part of the total settlement of highly organic deposits or old sanitary landfill sites.

(2) Because the degree of consolidation and applied stress vary with depth, it is necessary to determine if excess pore pressures will remain at any depth after surcharge removal. If so, further primary consolidation settlement under permanent loadings would occur. To avoid this occurrence, determine the duration of the surcharge loading required for points most distant from drainage boundaries.

(3) The rate and amount of preload may be controlled by the strength of the underlying soft soil. Use berms to maintain foundation stability and place fill in stages to permit the soil to gain strength from consolidation. Predictions of the rates of consolidation strength and strength gain should be checked during fill placement by means of piezometers, borings, laboratory tests, and in situ strength tests.

c. Vertical drains.

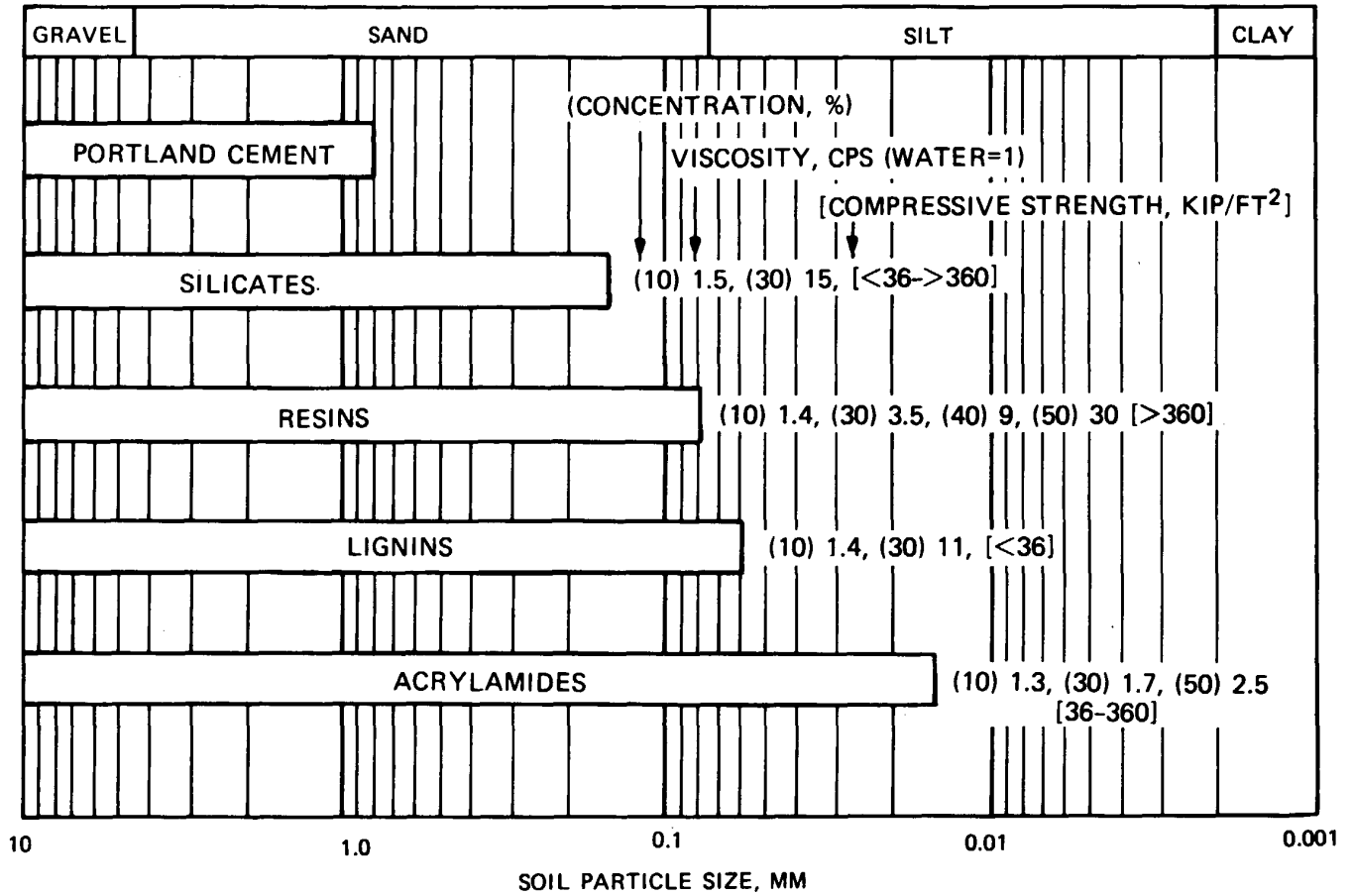
(1) The required preloading time for most soft clay deposits more than about 5 to 10 feet thick will be large. The consolidation time may be reduced by providing a shorter drainage path by installing vertical sand drains. Sand drains are typically 10 to 15 inches

in diameter and are installed at spacings of 5 to 15 feet. A sand blanket or a collector drain system is placed over the surface to facilitate drainage. Other types of drains available are special cardboard or combination plastic-cardboard drains. Provisions should be made to monitor pore pressures and settlements with time to determine when the desired degree of precompression has been obtained.

(2) Both displacement and nondisplacement methods have been used for installing sand drains. Although driven, displacement drains are less expensive than augered or "bored" nondisplacement drains; they should not be used in sensitive deposits or in stratified soils that have higher hydraulic conductivity in the horizontal than in the vertical direction. Vertical drains are not needed in fibrous organic deposits because the hydraulic conductivity of these materials is high, but they may be required in underlying soft clays.

d. Dynamic consolidation (heavy tamping). Densification by heavy tamping has also been reported as an effective means for improving silts and clays, with preconstruction settlements obtained about 2 to 3 times the predicted construction settlement. The time required for treatment is less than for surcharge loading with sand drains. The method is essentially the same as that used for cohesionless soils, except that more time is required. Several blows are applied at each location followed by a 1- to 4-week rest period, then the process is repeated. Several cycles may be required. In each cycle the settlement is immediate, followed by drainage of pore water. Drainage is facilitated by the radial fissures that form around impact points and by the use of horizontal and peripheral drains. Because of the necessity for a time lapse between successive cycles of heavy tamping when treating silts and clays, a minimum treatment area of 18,000 to 35,000 square yards (4 to 8 acres) is necessary for economical use of the method. This method is presently considered experimental in saturated clays.

e. Electroosmosis. Soil stabilization by electroosmosis may be effective and economical under the following conditions: (1) a saturated silt or silty clay soil, (2) a normally consolidated soil, and (3) a low pore water electrolyte concentration. Gas generation and drying and fissuring at the electrodes can impair the efficiency of the method and limit the magnitude of consolidation pressures that develop. Treatment results in nonuniform changes in properties between electrodes because the induced consolidation depends on the voltage, and the voltage varies between anode and cathode. Thus, reversal of electrode polarity may be desirable to achieve a more uniform stress condition. Electroosmosis may also be used to accelerate the consolidation under a preload or surcharge fill. The method is relatively expensive.



U. S. Army Corps of Engineers

Figure 16-6. Soil particle sizes suitable for different grout types and several concentrations and viscosities shown.

16-6. Reinforcement. The supporting capacity of soft, compressible ground may be increased and settlement reduced through use of compression reinforcement in the direction parallel to the applied stress or tensile reinforcement in planes normal to the direction of applied stress. Commonly used compression reinforcement elements include mix-in-place piles and walls. Strips and membranes are used for tensile reinforcement, with the latter sometimes used to form a moisture barrier as well.

a. Mix-in-place piles and walls. Several procedures are available, most of them patented or proprietary, which enable construction of soil-cement or soil-lime in situ. A special hollow rod with rotating vanes is augered into the ground to the desired depth. Simultaneously, the stabilizing admixture is introduced. The result is a pile of up to 2 feet in diameter. Cement, in amounts of 5 to 10 percent of the dry soil weight, is best for use in sandy soils. Compressive strengths in excess of 200 kips per square foot can be obtained in these materials. Lime is effective in both expansive plastic clays and in saturated soft clay. Compressive strengths of about 20 to 40 kips per square foot are to be expected in these materials. If overlapping piles are formed, a mix-in-place wall results.

b. Vibroreplacement stone columns. A vibroflot is used to make a cylindrical, vertical hole under its own weight by jetting to the desired depth. Then, 1/2- to 1- cubic yard coarse granular backfill, usually gravel or crushed rock 3/4 to 1 inch is dumped in, and the vibroflot is used to compact the gravel vertically and radially into the surrounding soft soil. The process of backfilling and compaction by vibration is continued until the densified stone column reaches the surface.

c. Strips and membranes.

(1) Low-cost, durable waterproof membranes, such as polyethylene, polypropylene asphalt, and polyester fabric asphalt, have had application as moisture barriers. At the same time, these materials have sufficient tensile strength that when used in envelope construction, such as surrounding a well-compacted, fine-grained soil, the composite structure has a greater resistance to applied loads than conventional construction with granular materials. The reason is that any deformation of the enveloped soil layer causes tension in the membrane, which in turn produces additional confinement on the soil and thus increases its resistance to further deformation.

(2) In the case of a granular soil where moisture infiltration is not likely to be detrimental to strength, horizontally bedded thin, flat metal or plastic strips can act as tensile reinforcing elements. Reinforced earth has been used mainly for earth retaining structures; however, the feasibility of using reinforced earth slabs to improve the bearing capacity of granular soil has been demonstrated.

(3) Model tests have shown that the ultimate bearing capacity can be increased by a factor of 2 to 4 for the same soil unreinforced. For these tests, the spacing between reinforcing layers was 0.3 times the footing width. Aggregate strip width was 42 percent of the length of strip footing.

d. Thermal methods. Thermal methods of foundation soil stabilization, freezing or heating, are complex and their costs are high.

(1) *Artificial ground freezing.* Frozen soil is far stronger and less pervious than unfrozen ground. Hence, artificial ground freezing has had application for temporary underpinning and excavation stabilization. More recent applications have been made to back-freezing soil around pile foundations in permafrost and maintenance of frozen soil under heated buildings on permafrost. Design involves two classes of problems; namely, the structural properties of the frozen ground to include the strength and the stress-strain-time behavior, and thermal considerations to include heat flow, transfer of water to ice, and design of the refrigeration system.

(2) *Heating.* Heating fine-grained soils to moderate temperatures, e.g., 100°C+, can cause drying and accompanying strength increase if subsequent rewetting is prevented. Heating to higher temperatures can result in significant permanent property improvements, including decreases in water sensitivity, swelling, and compressibility; and increases in strength. Burning of liquid or gas fuels in boreholes or injection of hot air into 6- to 9-inch-diameter boreholes can produce 4- to 7-foot-diameter strengthened zones, after continuous treatment for about 10 days. Dry or partly saturated weak clayey soils and loess are well suited for this type of treatment, which is presently regarded as experimental.

16-7. Miscellaneous methods.

a. Remove and replace. Removal of poor soil and replacement with the same soil treated by compaction, with or without admixtures, or by a higher quality material offer an excellent opportunity for producing high-strength, relatively incompressible, uniform foundation conditions. The cost of removal and replacement of thick deposits is high because of the need for excavation and materials handling, processing, and recompaction. Occasionally, an expensive dewatering system also may be required. Excluding highly organic soils, peats and sanitary landfills, virtually any inorganic soil can be processed and treated so as to form an acceptable structural fill material.

b. Lime treatment. This treatment of plastic fine-

grained soils can produce high-strength, durable materials. Lime treatment levels of 3 to 8 percent by weight of dry soil are typical.

c. *Portland cement.* With treatment levels of 3 to 10 percent by dry weight, portland cement is particularly well suited for low-plasticity soils and sand soils.

d. *Stabilization using fills.*

(1) At sites underlain by soft, compressible soils and where filling is required or possible to establish the final ground elevation, load-bearing structural fills can be used to distribute the stresses from light structures. Compacted sands and gravels are well suited for this application as are also fly ash, bottom ash, slag, and various lightweight aggregates, such as expanded shale, clam and oyster shell, and incinerator ash. Admixture stabilizers may be incorporated in these materials to increase their strength and stiffness.

(2) Clam and oyster shells as a structural fill material over soft marsh deposits represent a new development. The large deposits of clam and oyster or reef shells that are available in the Gulf States coastal areas can be mined and transported short distances economically. Clam shells are 1/4, to 1/2 inch in diameter; whereas, oyster shells, which are coarser and more elongated, are 2 to 4 inches in size. When dumped over soft ground, the shells interlock; if there are fines and water present, some cementation develops owing to the high calcium carbonate (>90 percent) content. In the loose state, the shell unit weight is about 63 pounds per square foot; after construction, it is about 95 pounds per square foot. Shell embankments "float" over very soft ground; whereas, conventional fills would sink out of sight. About a 5-foot-thick layer is required to be placed in a single lift. The only compaction used is from the top of the lift, so the upper several inches are more tightly knit and denser than the rest of the layer.